Heavy Flavor Production and Spectroscopy with CDF

Prabhakar Palni
(On behalf of the CDF Collaboration)

Department of Physics & Astronomy,
University of New Mexico, USA

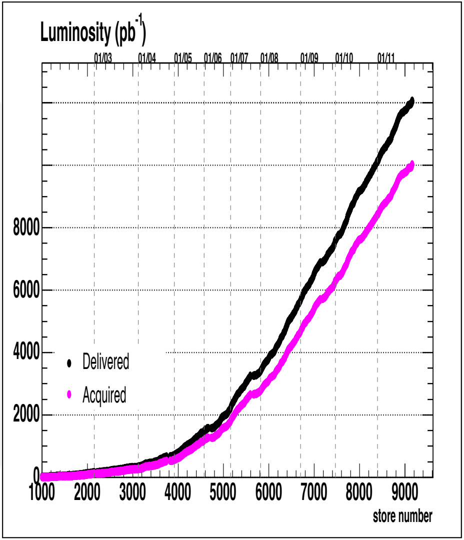
BEACH 2012
Wichita, Kansas, 23-28 July, 2012

Outline of the talk

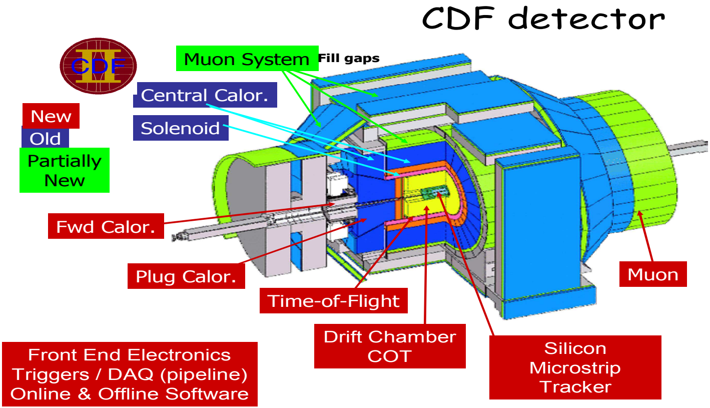
- The Tevatron and the CDF II Detector
- Confirmation of the Bottom Baryon Resonance state Λ_b^{*0}
- Probing Quark Fragmentation
- Upsilon Spin Alignment

Statistics

- The Tevatron collided p with $\overline{p}$ at 1.96TeV center of mass energy from 2001-2011
- Instantaneous Luminosity $4x10^{32} cm^{-2} s^{-1}$
- $\int \mathcal{L}\, dt \simeq 12.0\,\text{fb}^{-1}$ delivered
- $\int \mathcal{L}\, dt \simeq 10.0\,\text{fb}^{-1}$ on tape, accessible for **CDF II**



CDF Detector



- Silicon Vertex Detector, Drift Chamber and TOF detector
- B=1.4T and 1.5σ separation between kaon and pion from TOF + dE/dX

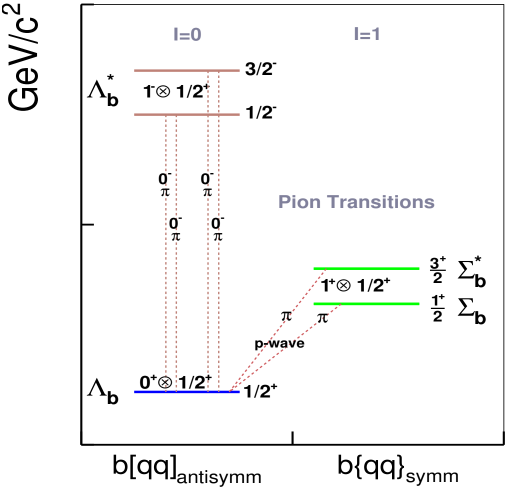
Confirmation of the Bottom Baryon Resonance State Λ_b^{*0}

CDF Public Note 10900

Motivation

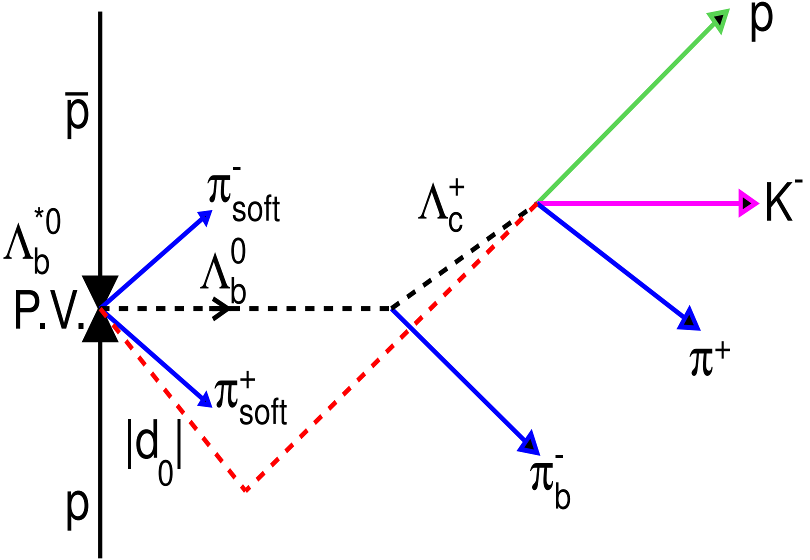
- Heavy hadrons are the "helium atoms of QCD" where the nucleus is the heavy quark Q and the two orbiting electrons are the light diquark qq
- Measurements of the masses and widths of the heavy baryons provide input to test different non-perturbative QCD approaches to the spectroscopy of bottom hadron states
  For example: Heavy Quark Effective Theory (HQET) and Lattice QCD
- Λ_b^{*0} is a resonance state containing the quarks b, u, and d. LHCb has recently observed this state with a signal significance greater than 5σ(*arXiv:1205:3452[hep-ex]*)
- **Goal of the analysis: Search for the Λ_b^{*0} resonant state through its decay to $\Lambda_b^0\pi^+\pi^-$**

Resonant States Decaying into Λ_b^0 Singlet



- Λ_b^{*0}, Orbital excitations: $J^P = (1/2)^-$and $(3/2)^-$ (Strong decay)
- Λ_b^0, Singlet state: $J^P = (1/2)^+$ (Weak-decay)
- pions $\pi^+\pi^-$ are soft and emitted in p-wave

Decay Chain of Λ_b^{*0}



Masses and Q-values of Λ_b^{*0} Resonance States

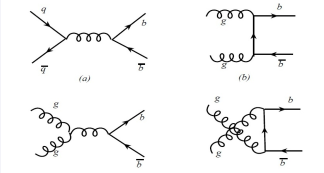
- $Q \equiv$ M($\Lambda_b^{*0} \to \Lambda_b^0\pi^+\pi^-$) - M($\Lambda_b^0$) - 2m($\pi^\pm$)
  i.e the amount of energy released by the decay reaction
- Various theoretical models predict that the mass of the first excited state $\Lambda_b^{*0}, (1/2)^-$ lies very close to the hadronic three-body mode threshold with Q≡[20...47] MeV/c^2
- The higher excited state, $\Lambda_b^{*0}(3/2)^-$has Q≡[2...17] MeV/c^2 higher than the lower state.

Two Displaced Track Trigger

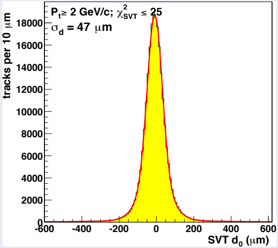
b-Triggers at @1.96 TeV

- Enormous inelastic total cross-section of $\sigma_{\mathbf{tot}}^{\mathbf{inel}} \sim \mathbf{60}\,\mathrm{mb}$
- $\sigma_{\mathbf{b}} \approx \mathbf{20}\,\mu\mathrm{b}\,(|\eta| < \mathbf{1.0})$, @1.96 TeV
- **Trigger on Hadronic Modes: CDF Two Track Trigger**
  - Exploit long $c\tau$ (b-hadrons)
  - Trigger on $\geq$ 2 tracks with large $|d_0|$
  - $p_T \geq$ 2 GeV/c

(b production in $p\bar{p}$)



$|d_0|$ Resolution $\oplus$ beam-line = 47 μm



Signal Model

We reconstruct Λ_b^{*0} candidates in the mass difference spectrum: Q-value

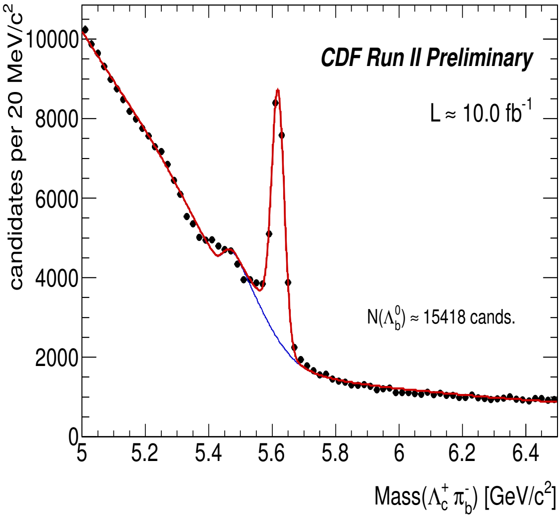
$$Q = M(\Lambda_b^{*0} \rightarrow \Lambda_b^0 \pi^+ \pi^-) - M(\Lambda_b^0) - 2m(\pi^{\pm}_{PDG})$$

- Mass resolution of Λ_b^0 and most of the systematic uncertainties cancel leaving only the $\pi^+_{soft}\pi^-_{soft}$ contribution.

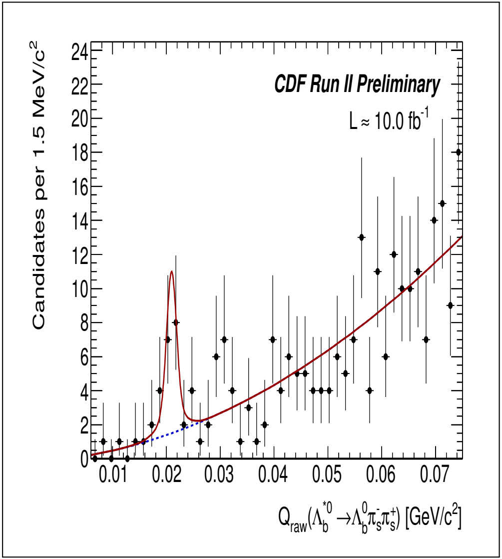
- The signal is described by a double Gaussian to model detector resolution.
- Signal shape is fixed from the MC sample.
- The background is described by a second order Chebyshev polynomial.
- Q-value spectrum is obtained using full, Signal + Background model.
- Used high statistics CDF $D^{*+} \rightarrow D^0 \pi^+_{soft}$ sample to gauge the soft pion momentum scale for Λ_b^{*0} soft pion candidates.
  - Scale is adjusted by: $Q(\Lambda_b^{*0}) = Q(\Lambda_b^{*0}) - 0.28$ MeV/c^2

Analysis Criteria

- Exploit long life time and large mass of Λ_b^0
- $p_T(\Lambda_b^0) > 9.0\,\mathrm{GeV}/c$ (Large)
- $c\tau(\Lambda_b^0)/\sigma_{c\tau} > 6.0$
- $p_T(\pi_b^-) > 1\,\mathrm{GeV}/c$
- $p_T(\pi_{soft}^{\pm}) > 0.2\,\mathrm{GeV}/c$
- $|d_0/\sigma_{d_0}|(\pi_{soft}^{\pm}) < 3.0$, w.r.t. primary VX.



Q-value spectrum of Λ_b^{*0}



The projection of the unbinned maximum LH fit onto the binned Q-value raw distribution of Λ_b^{*0} candidates

- Number of signal events $= 17^{+5.3}_{-4.6}$
- $Q(\Lambda_b^{*0}) = 20.68 \pm 0.35$ MeV/c^2 , Q-value scale adjustment applied.

Significance of the Signal

Local Significance Estimate Based on Exp. Data Fits

- Signal + Background,$\mathcal{H}_1$ (Signal Hypothesis).
- Background only,$\mathcal{H}_0$(Null Hypothesis).
- D= $-2{*}\ln\frac{\mathcal{L}_1}{\mathcal{L}_0} = -2 * \triangle(\mathit{In}\mathcal{L})$
- p-value is $2.28 * 10^{-6}$
- Significance of the signal is 4.6σ

Significance Estimated with toy MC expts.

- Generate Null Hypothesis $\mathcal{H}_0$, fit with $\mathcal{H}_1$
- Parameter of interest , N_{cands}
- Signal position Q left floating within [6,50] MeV/c^2 search window
- Signal shape fixed
- Background shape floating
- p-value = $2.3 * 10^{-4}$ or 3.5σ

Systematic Uncertainties on Q-value

Source	**Value**, MeV/c^2	**Comment**
Momentum scale	± 0.28	propagated from high statistics calibration D^{*+} sample; 100% of the found adjustment value.
Signal model	± 0.11	MC underestimates the resolution; choice of the model's parameters
MC resolution stat. uncertainty	± 0.012	finite MC sample size induces the stat. uncertainty of the shape parameters.
Background model	± 0.03	consider 3-rd, 4-th power polynomials
Total:	± 0.30	added in quadrature

Summary of Results

To determine the absolute mass of the Λ_b^{*0}

- M $(\Lambda_b^0) = 5619.7 \pm 1.2(stat) \pm 1.2(syst)$ MeV/c^2

Measured Properties of the Λ_b^{*0} for $\int \mathcal{L}\, dt \simeq 10.0\,\mathrm{fb}^{-1}$

Value	MeV/c^2
Q	$20.68 \pm 0.35(\mathrm{stat}) \pm 0.30(\mathrm{syst})$
ΔM	$299.82 \pm 0.35(\mathrm{stat}) \pm 0.30(\mathrm{syst})$
$\mathrm{M}(\Lambda_b^{*0})$	$5919.5 \pm 0.35\,(\mathrm{stat}) \pm 1.72\,(\mathrm{syst})$

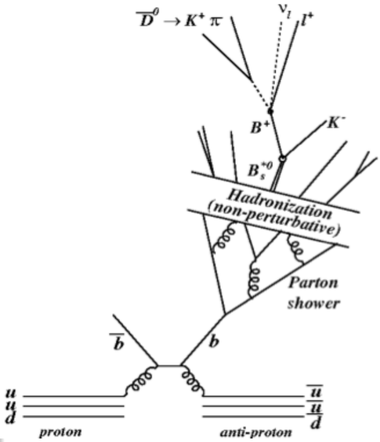
- CDF Public Note 10900

Probing Quark Fragmentation

CDF Public Note 10704

Quark Fragmentation

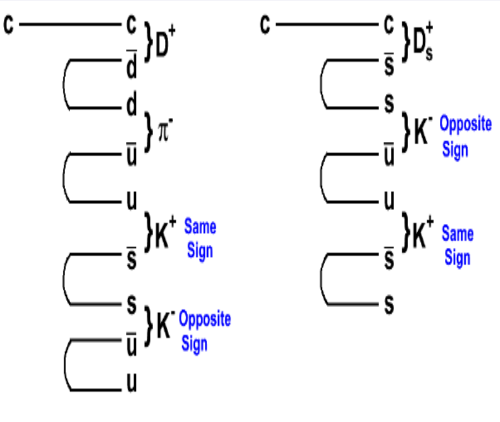
- Quark fragmentation models, string and cluster fragmentation
- D mesons offer solid and data based technique to validate these models
- Study charged particle production around heavy quarks
  - Kaons near D_s and D^+ both decaying to $\phi\pi$
  - Similar technique used by B_s flavor
- D used for fragmentation studies
  - No known resonances decay to D_sK
  - Charged D's do not mix
  - Select prompt D's to minimize contamination from B–>DX decays



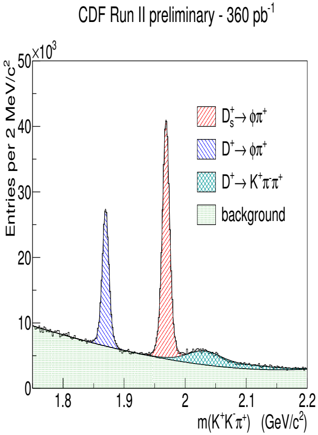
Probing Fragmentation

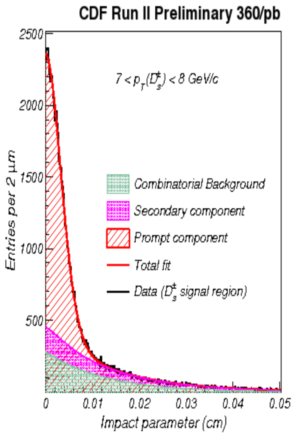
Charge Correlation between D and K

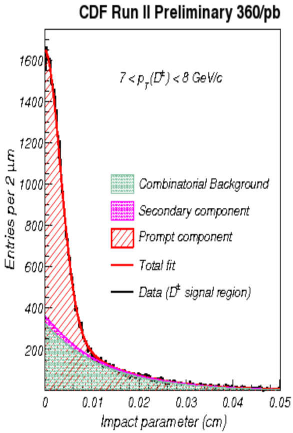
- For D_s^+:
  - Opposite sign $\Rightarrow$ early in fragmentation chain
  - Same sign $\Rightarrow$ late in fragmentation chain
- For D^+:
  - Random charge correlation



Methodology

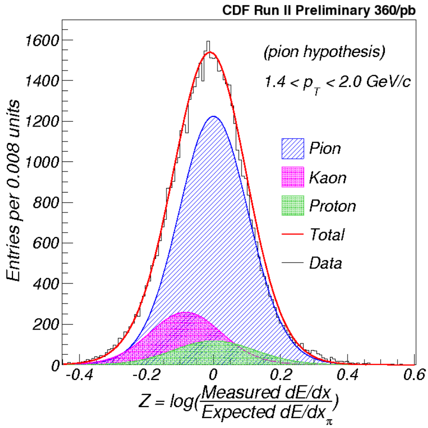


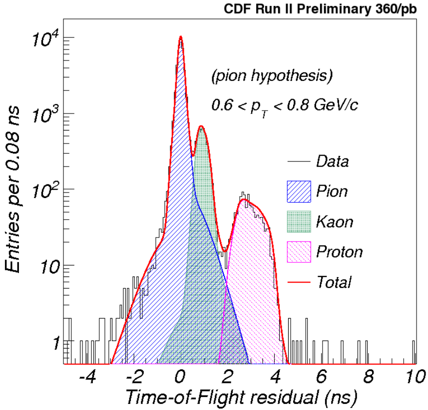




- Prompt $D_s^\pm/D^\pm$ mesons have ideally zero IP compared to finite IP of secondary components.

Methodology

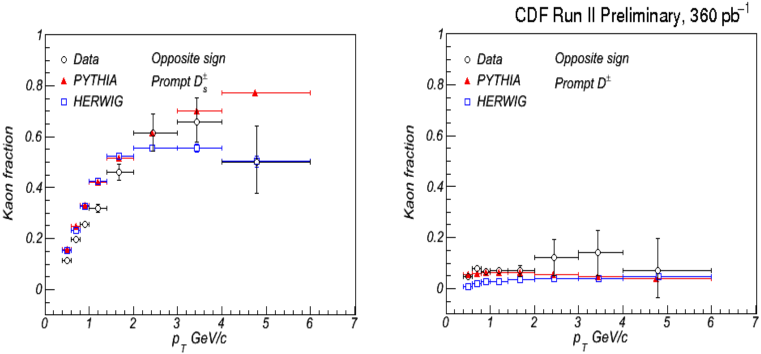




Particle Identification Techniques

- Specific ionization per unit track length (dE/dX) in COT
- Time of Flight (TOF) of the particle measured in TOF sub-detector

Kaon Fraction Compared with Pythia and Herwig

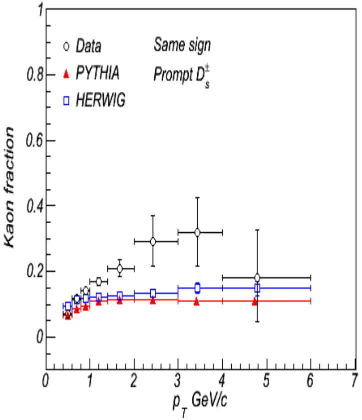


Measure kaon fraction with likelihood fit

- Take maximum p_T tracks in $\triangle$ R=0.7 cone around D candidates

- Kaon production around prompt $D_s^\pm$ is enhanced compared to prompt $D^\pm$ in the opposite sign combination

Kaon Fraction Compared with Pythia and Herwig



- Kaon production in the same sign combination is similar around prompt $D_s^{\pm}$ and prompt $D^{\pm}$

Upsilon Spin Alignment

Phys. Rev. Lett. 108, 151802 (2012)

Upsilon spin-alignment

Discrepancies in previous Upsilon spin alignment study

- Differences between CDF and D0 results (Υ polarized?)
- Measurement of spin alignment in s-channel helicity frame only

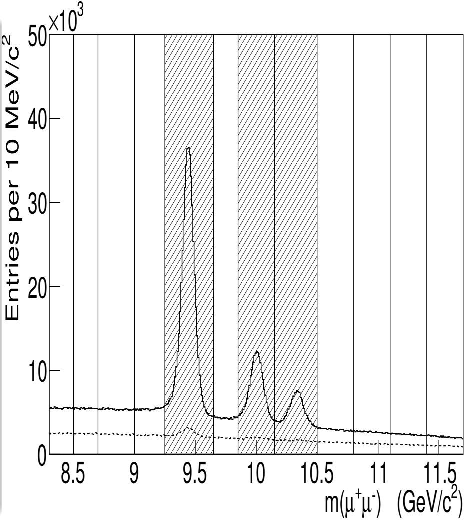
Angular distribution of muons from Υ decays

$$\frac{d\Gamma}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

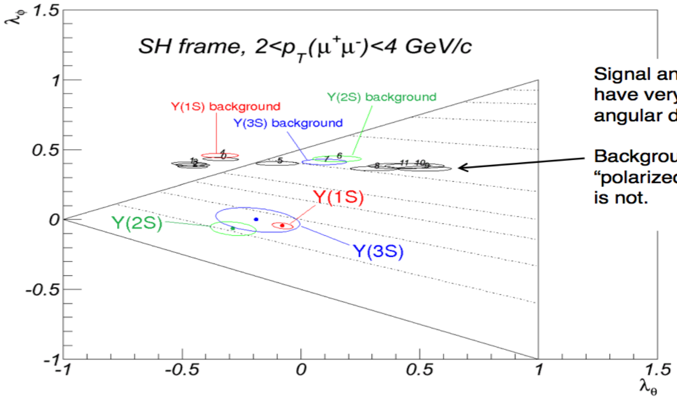
- Previous experiments have only measured λ_θ
  - Does not allow to calculate rotationally invariant quantities
  - Bias could be introduced for non-uniform detector acceptance in ϕ
- This measurement is the first that determines the full 3D angular distribution

Invariant Mass Distribution of Dimuon events

- 550k Υ(1S), 150k Υ(2S), 76k Υ(3S) decaying into $\mu^+\mu^-$
- Background is dominated by muons from b-decays
- B enriched sample from displaced muons is used to model the angular distribution of the background
- Obtain geometric acceptance from MC sample
- Combined momentum resolution is $\sigma_{p_t}/p_t^2 \sim 0.07\%$



Results

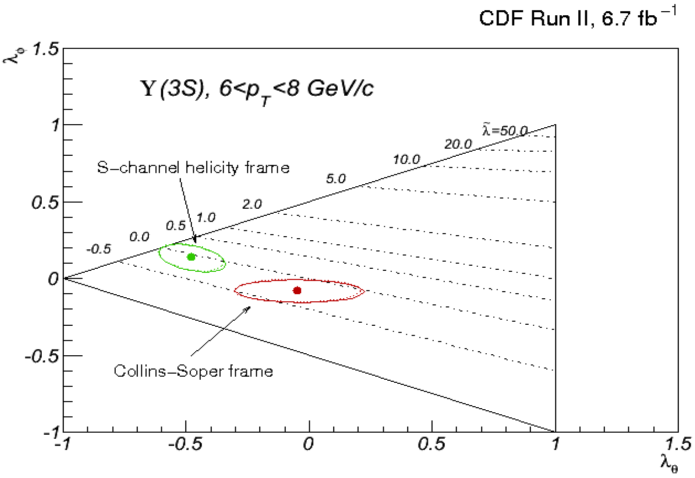


Signal and background have very different angular distributions.

Background is highly "polarized" but the signal is not.

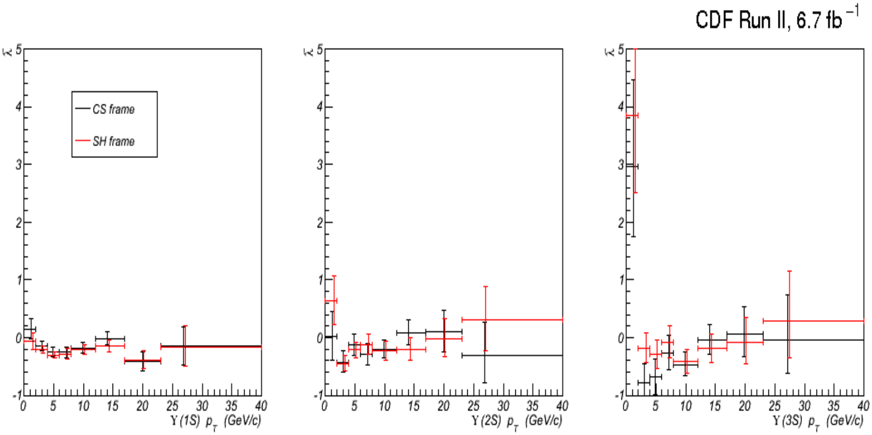
- First measurement of $\Upsilon(3S)$ parameters
- None of the 3 states shows evidence of polarization
- Verified with frame invariance crosschecks

Results



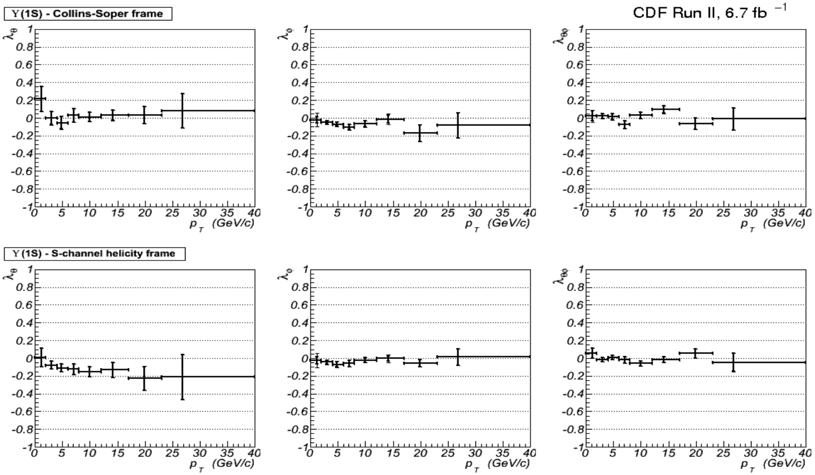
- One-sigma confidence intervals for λ_θ and λ_φ for the $\Upsilon(3S)$ state

Comparison of rotationally invariant quantity, $\tilde{\lambda}$



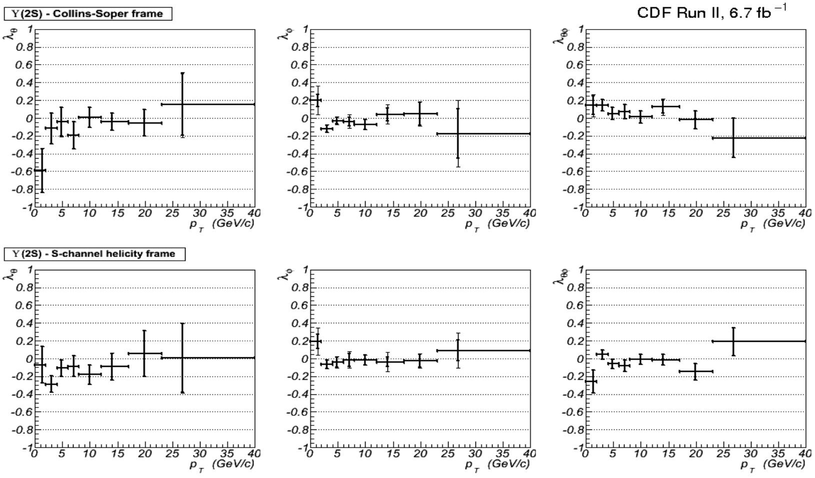
- Rotationally invariant quantity $\tilde{\lambda}$ in CS and SH frame
  $\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\varphi}{1-\lambda_\varphi}$

Results



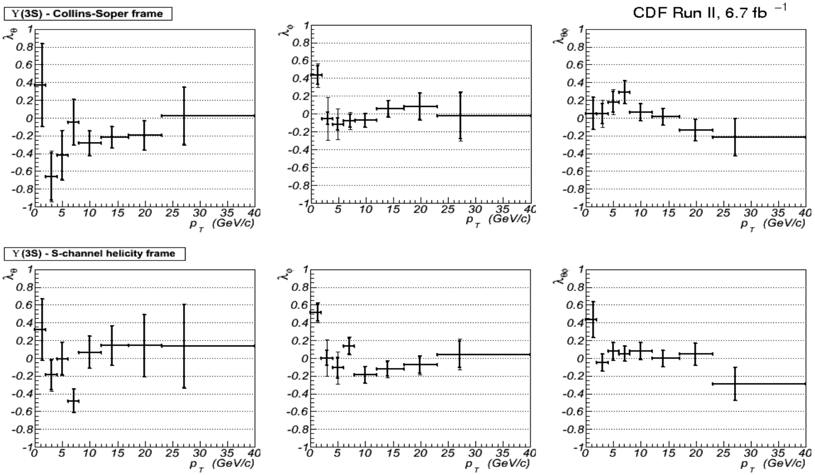
- Comparison of $\lambda_\theta, \lambda_\varphi$ and $\lambda_{\theta\varphi}$ as a function of p_T for $\Upsilon(1S)$ state

Results



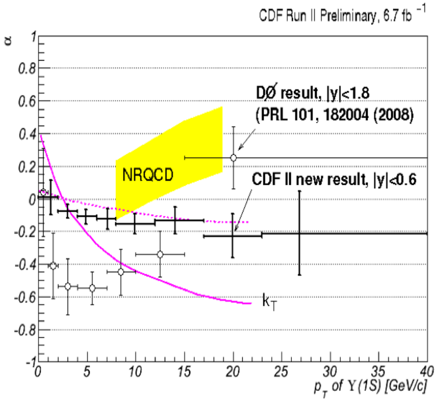
- Comparison of $\lambda_\theta, \lambda_\varphi$ and $\lambda_{\theta\varphi}$ as a function of p_T for $\Upsilon(2S)$ state

Results

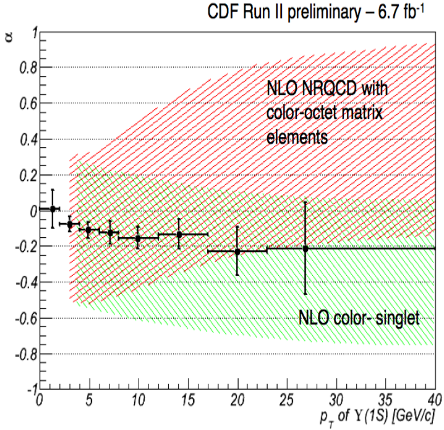


- Comparison of $\lambda_\theta, \lambda_\varphi$ and $\lambda_{\theta\varphi}$ as a function of p_T for $\Upsilon(3S)$ state

Comparison with Theoretical Models



NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)
k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)



- Comparison of $\alpha \equiv \lambda_\theta$ for $\Upsilon(1S)$ decays in the SH frame
- Newer theoretical calculations have larger uncertainties

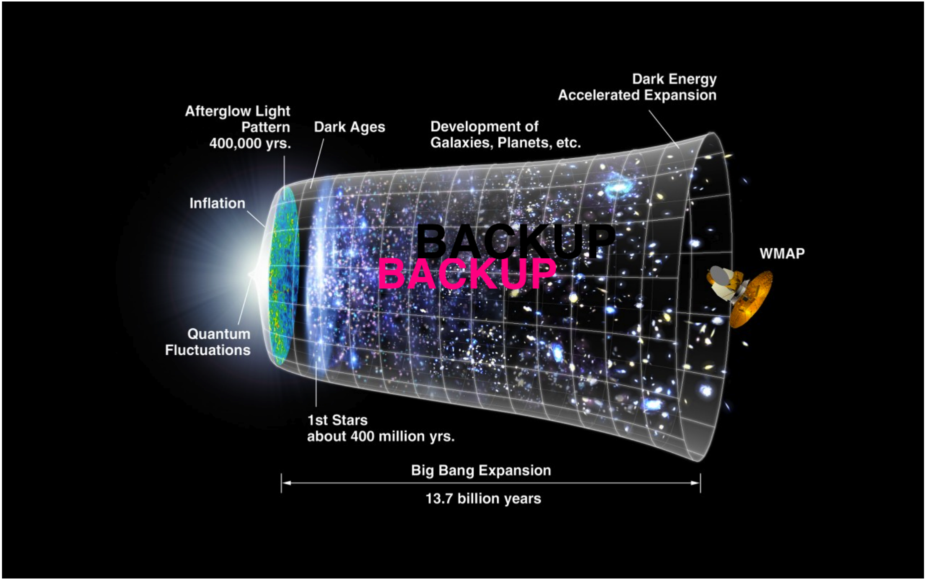
Summary and Conclusions

- The Λ_b^{*0} resonance is observed by the CDF at Q(Λ_b^{*0}) = 20.68 $\pm$ 0.35 MeV/c^2 with the significance of the signal 3.5σ and the local signal significance of 4.6σ
- Confirms one of the states recently observed by the LHCb Collaboration

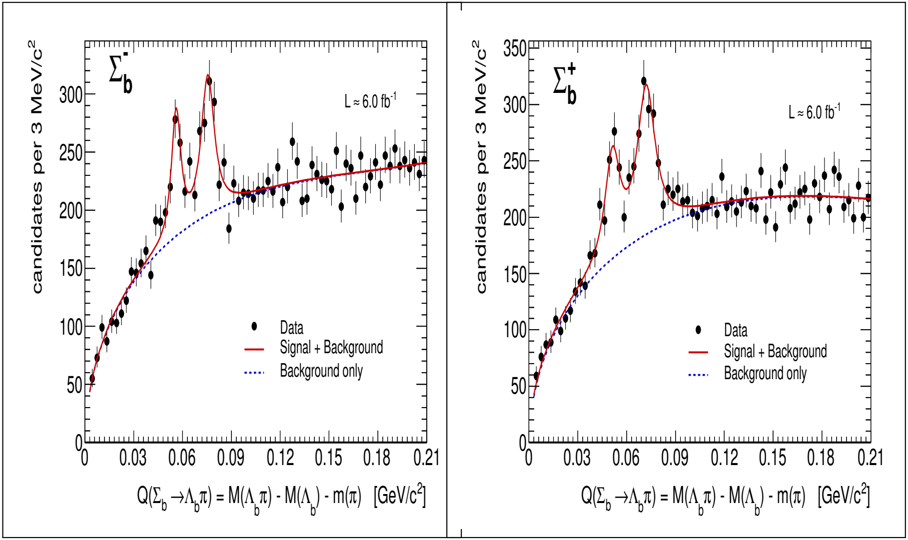
- For opposite sign charge combination: kaon production around prompt $D_s^{\pm}$ is enhanced compared to production around prompt $D^{\pm}$
- MCs are consistent in describing early production of kaons, but description of kaon production later in the fragmentation is inadequate

- First 3D measurement of Υ(3S) parameters
- No significant evidence of polarization for $\Upsilon(nS)$ over a wide range of p_T

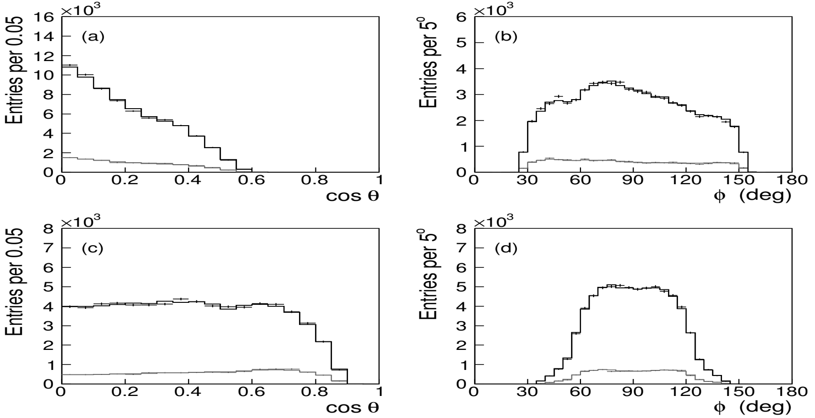

THANK
YOU


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
BACKUP
BACKUP
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

$\Sigma_*^{\pm}$ in CDF: PRD 85, 092011 (2012)

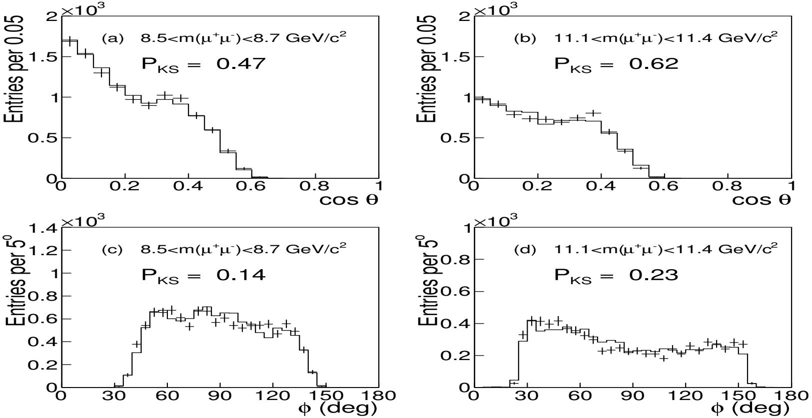


Results



- Projections of angular variables measured in the CS and the SH frames for the range of invariant mass containing the $\Upsilon(1S)$ signal

Results



- Comparisons of projected angular distributions measured in the CS frame for prompt and displaced (error bars) dimuon samples in the low-mass and high-mass sidebands

Systematic Uncertainties

- Momentum Scale: B field knowledge, uncertainty due to detector material on the dE/dx correction.
- Detector resolution model and its parameters.
(Detector resolution is a critical parameter for our measurements especially for the fits of natural widths)
- Choice of the background model.
- Systematics propagated from the previous CDF measurement of the Λ_b^0 mass.

Theoretical Predictions of Masses and Q-value

References	$M(\Lambda_b^0)$ MeV/c^2	$M(\Lambda_b^{*0}, 1/2^-)$ MeV/c^2	Q MeV/c^2	$M(\Lambda_b^{*0}, 3/2^-)$ MeV/c^2	Q MeV/c^2
Capstick [1]	5585	5912	47	5920	55
Karliner [2]	5619.7	5929	29	5940	40
Roberts [3]	5612	5939	47	5941	49
Garcilazo [4]	5625	5890	-15	5890	-15
Faustov [5]	5622	5930	28	5947	45
Zhang [6]	5690	5850	-120	5900	-70
Aziza B. [7]	5619.7	5920	20	5920	20

- $Q \equiv$ M($\Lambda_b^{*0} \to \Lambda_b^0 \pi^+ \pi^-$) - M($\Lambda_b^0$) - 2m($\pi^{\pm}_{PDG}$)
- The predicted masses for the first excited state lie very close to the hadronic three-body mode threshold with Q≡[20...47] MeV/c^2 and for its higher excited state with only Q≡[2...17] MeV/c^2 higher.

[1]S. Capstick, et al. Phys. Rev. D **34**, 2809 (1986) [2]M. Karliner,et al, arXiv:0708.4027. [3]W. Roberts et al., Int. J. Mod. Phys. A **23**, 2817 (2008) [4]H. Garcilazo,et al. J. Phys. G **34**, 961 (2007) [5]D. Ebert, et al. Phys. Rev. D **72**, 034026 (2005) [6]J. R. Zhang, et al. Phys. Rev. D **78**, 094015 (2008) [7]Z. Aziza Baccouche et al. Nucl. Phys. A **696**, 638 (2001)

References to the Predictions of Masses and Q-value

- [1]S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).
- [2]M. Karliner, B. Keren-Zur, H. J. Lipkin and J. L. Rosner, arXiv:0708.4027 [hep-ph].
- [3]W. Roberts and M. Pervin, Int. J. Mod. Phys. A **23**, 2817 (2008) [arXiv:0711.2492 [nucl-th]].
- [4]H. Garcilazo, J. Vijande and A. Valcarce, J. Phys. G **34**, 961 (2007) [arXiv:hep-ph/0703257].
- [5]D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D **72**, 034026 (2005) [arXiv:hep-ph/0504112].
- [6]J. R. Zhang and M. Q. Huang, Phys. Rev. D **78**, 094015 (2008) [arXiv:0811.3266 [hep-ph]].
- [7]C. K. Chow and T. D. Cohen, Nucl. Phys. A **688**, 842 (2001) [arXiv:hep-ph/0003131].

The Tevatron Accelerator at Fermilab near Chicago